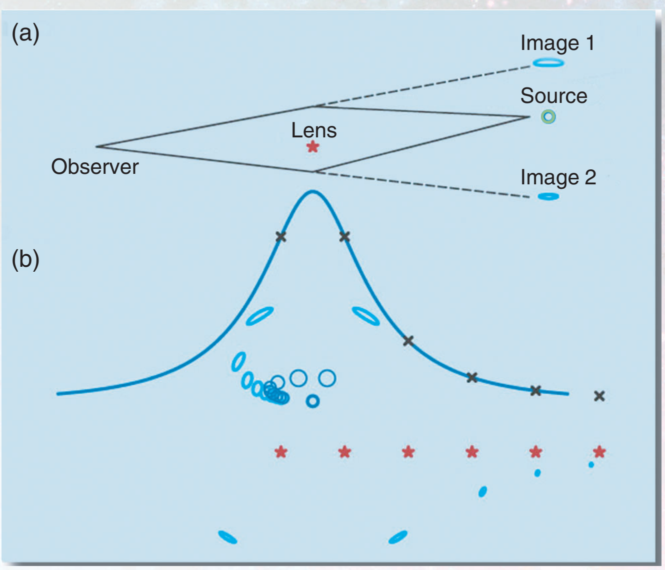
A New Way to Measure the Mass of Stars

WHEN an international collaboration began a search for dark matter in the Milky Way Galaxy, measuring a star's mass was not the goal they had in mind. But as the team examined more closely the massive compact halo objects (MACHOs) they had found, they realized that all the information they needed for measuring a single, isolated stellar mass was right in front of them.

Measuring the mass of a star or a satellite such as planets or moons used to be a relative affair: How does the presence of one body affect the position of the other? The movement of the Sun as the Earth and other planets revolve around it is largely a function of their relative masses. The same is true for our Moon as it revolves around our home planet. New discoveries about the existence of planets around other stars are inferred by observing wobble in a star's position. More wobble means more mass is revolving around it. Careful observations of the wobble can reveal how many planets are acting on the star.

Astrophysicist Kem Cook, who leads the Livermore contribution to the team, notes, "Measuring the mass of a star has never been possible when it was in physical isolation. Always before, we were looking at two bodies—the Sun and Earth or binary stars. Now we can do just one, but it takes lots of time and data."



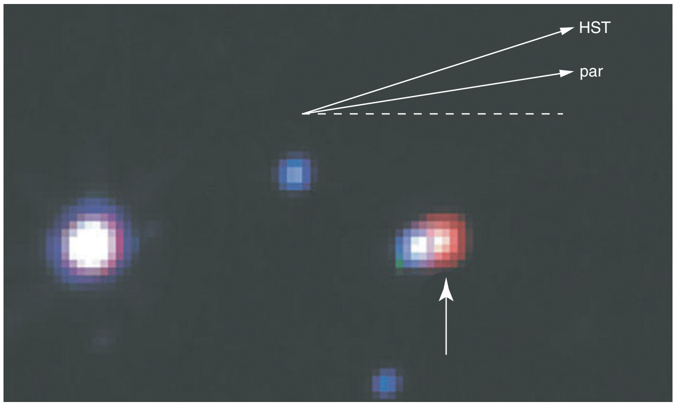
A step-by-step guide to gravitational microlensing. (a) Light from the source star (green) is deflected by the lens (red), creating two enlarged and distorted images (blue). (b) As the lens passes in front of the source, the pair of images becomes first larger and then smaller, so that the observed light flux (blue curve) becomes brighter and then fainter.

The Critical Image

From 1992 to 2000, the MACHO collaboration, including researchers from the U.S., Australia, Chile, Germany, Britain, and Canada, searched the outer regions of the Milky Way for MACHOs using the Large Magellanic Cloud (LMC) as a backdrop (see the box on p. 22). They were looking for events in which the gravitational field of a MACHO came between their detector and a distant star, causing the distant star to brighten significantly. Gravity acts as a lens in a process called microlensing. Six years of observational data have been analyzed thus far, revealing 17 microlensing events in the Milky Way's halo, including the first event ever positively identified.

Of particular interest was the brightest event, known as LMC-5. The distant, or source, star became at least 15 times brighter when it was behind the microlensing object. The unmagnified color of the patch of sky occupied by both the lens and the source star was redder before and after the peak of the microlensing event. Researchers suspected that the source star was a blue star in the LMC that, because of atmospheric blurring, was confused with a red star, whose color and brightness suggested a red dwarf star in the Milky Way.

To better characterize the source stars of all microlensing events, the team obtained images taken by the Hubble Space Telescope, which operates well above Earth's atmosphere. The 1999 Hubble image for the LMC-5 region, taken 6.3 years



A three-color composite image from the Hubble Space Telescope (HST) of the brightest microlensing event. The microlensing source star is the blue star at the right of the figure, which is partially blended with a much redder object (indicated by the arrow) displaced by 0.134 arcseconds. The directions of motion of the lens on the sky derived from the HST (–92 degrees) and from the unconstrained parallax (par) fit (–100 degrees) are shown.

after the peak of the LMC-5 microlensing event in February 1993, revealed a faint red object in addition to the source star. The two stars were still so close to one another that even on the Hubble image, they appeared slightly blended.

The team went back to reexamine the details of the LMC-5 microlensing curve. By analyzing perturbations in the curve caused by Earth's movement around the Sun, they were able to predict the direction that the lens would move across the sky. They found that the red star shown in the Hubble image was in the place that their calculations predicted and must be the lens. But the team didn't stop there.

Adding It All Up

Over 30 years ago, researchers suggested that gravitational microlensing could be used to measure the masses of nearby stars, although no one had yet seen a microlensing event in action.

Data collected in microlensing events are insufficient to measure the mass of the lens: The duration is proportional to the mass of the lens, the relative distances of the lens and the

The Search for MACHOs

Massive compact halo objects (MACHOs) are thought to be one kind of the invisible dark matter that surrounds and permeates our galaxy and other galaxies like it. Astronomers have determined that the Milky Way Galaxy must be much more massive than the amount of mass that is visible. Without the additional mass, the galaxy would fly apart. In fact, as much as 90 percent of the Milky Way's mass cannot be detected with available techniques. There is no question that dark matter exists. Finding it is the challenge.

Earlier studies suggested that MACHOs would produce gravitational microlensing, a process by which the gravity of one object comes between an observer and a distant star and causes the light of the distant star to be briefly magnified. Because a microlensing event requires that the two bodies be lined up almost perfectly, microlensing events are quite rare. Although a star could act as a microlens, the relative lack of stars in the outer regions of the Milky Way made it likely that any microlenses seen would prove to be MACHOs.

Using the Large Magellanic Cloud (LMC) Galaxy as a backdrop of distant, or source, stars, researchers from around the world searched for MACHO microlensing events with a special camera developed at Livermore. Scientists monitored millions of stars in the LMC at Mount Stromlo Observatory in Canberra, Australia, from 1992 to 2000. This observatory was chosen because the LMC is only visible from the southern hemisphere.

By observing whether the brightness of any source stars varied over time as a gravitational lens passed between the star and the observatory's detector, the team identified numerous microlensing events toward the Large Magellanic Cloud. Their data to date indicate that between 8 and 50 percent of the Milky Way's mass is in the form of MACHOs.

Using Hubble Space Telescope images to more closely examine the source stars of LMC microlensing events, the team has thus far found that only LMC-5 involved a visible star acting as a lens. All the rest were apparently caused by the gravitational field of a MACHO.

Astronomical research came to a screeching halt at the Mount Stromlo Observatory in January 2003 when a raging bush fire destroyed many buildings, including four telescopes, computers, and a spectrograph being constructed for the 8.2-meter Gemini North telescope in Mauna Kea, Hawaii. The fire destroyed about one-third of Australia's astronomical research program.

source star from Earth, and the motion of the lens across the line of sight of the source star.

With LMC-5, much more information was available, thanks to the image from the Hubble Space Telescope. “If we assume that the red star is the microlens and the other star is the source star, then we have a physical measurement on the sky of the motion of the lens,” says Cook.

The team had already determined the apparent direction and motion across the line of sight of the lens from the distortion in the light curve due to the motion of the Earth. Combining that information with the known distance to the Large Magellanic Cloud, which is very shallow, and the time between the original image and the Hubble image, allowed them to determine the distance the lens had traveled and, hence, its velocity. With the Hubble image—the first ever of a microlens scooting across the heavens—the team had all of the elements needed to determine the distance of the lens and its mass. They found that the mass of the LMC-5 lens was about one-tenth the mass of the Sun.

A Better Way Soon

An even better way to measure the mass of stars will be available in 2009 or so when National Aeronautics and Space Administration launches the Space Interferometry Mission (SIM). SIM will use optical interferometry to measure the tiny, apparent motion of stars, which is caused by microlensing, to determine the masses and distances of stars with much greater accuracy than previously possible. Measuring the mass of individual stars with data from SIM will be a veritable walk in the park.

—Katie Walter

Key Words: gravitational microlensing, massively compact halo objects (MACHOs).

For further information contact Kem Cook (925) 423-4634 (cook12@llnl.gov).